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Transparent Materials for Armor – A Cost Study



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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 11 JAN 2010		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Transparent Materials for Armor A Cost Study				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Lisa Prokurat Franks				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA				8. PERFORMING ORGANIZATION REPORT NUMBER 20473RC	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) TACOM/TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 20473RC	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 28	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

- **Background**
- **Current Demand Data**
- **Government Cost/Benefit Analysis**
- **Ballistic Depth of Penetration (DOP) Test**
- **Summary**

Cost Study Beginnings

- Sagamore Army Materials Research Conference
 - Began in 1954, each conference focuses on a materials-related topic
 - Provides a forum for scientists and engineers from academia, industry, and the government to discuss a different topic each time and its importance to the Army and the greater DOD materials communities
 - Past themes include risk and failure analysis, residual stress and stress relaxation, corrosion prevention and control
 - http://ammmtiac.alionscience.com/pdf/AMPQ9_2ART03.pdf
- Sagamore 2005 → *Transparent Materials*
 - Superior (new) materials for missile domes available for ~ 30 years, *but not used*
 - Once a material is in the “system”, replacement or substitution generally absent
 - Cost not performance dominates material selection decisions
- Challenge: *Develop a tool for decision makers to find the break-even cost point for materials that improve performance*

Initial Research Project

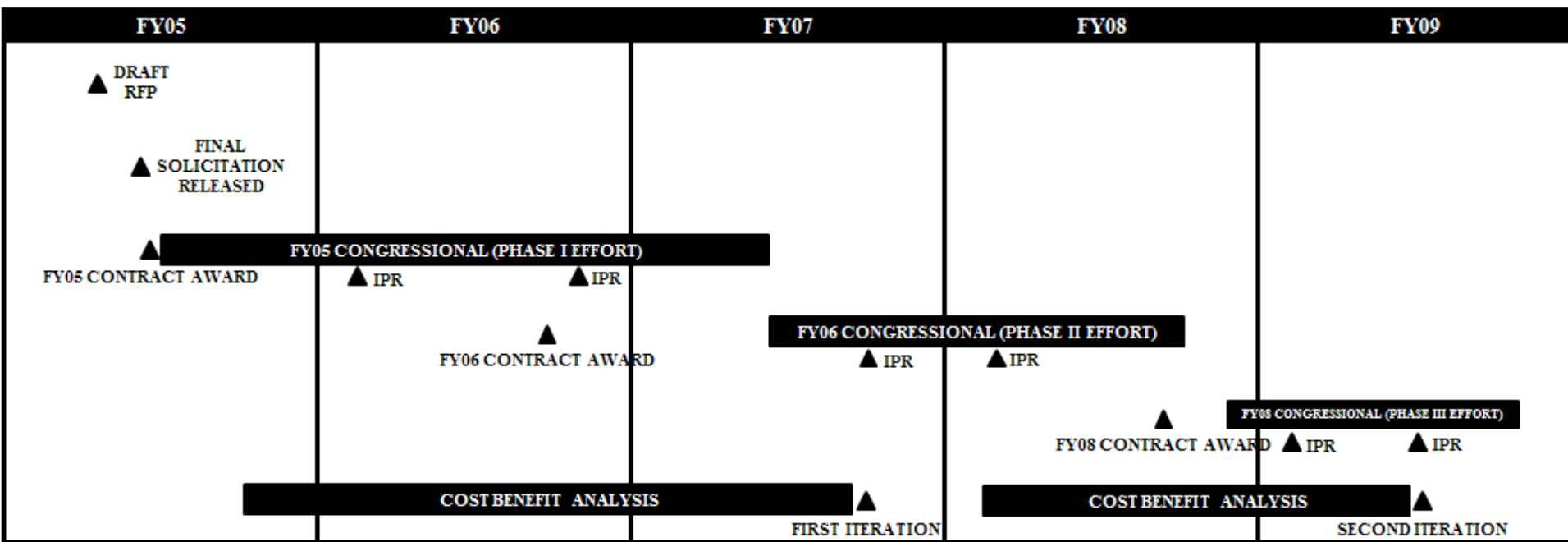
- Develop strong and damage tolerant transparent ceramics* for use in high performance armor/window/dome systems
- Materials considered or in-use for transparent armor applications
 - Ballistic glass
 - Al_2O_3 (single crystal, Sapphire)
 - AlON (ALON)
 - MgAl_2O_4 (Spinel)
 - $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG),
 - nanocrystalline Al_2O_3 (Alumina)
- Available “Commercial” Spinel
 - Non-optimal strength (avg <150 Mpa)
 - Large (>50 μm), bimodal grain structure

** With knowledge gained from 2005 Sagamore, this project appeared , although genuine and cutting edge, to be another “so what” exercise unless a concurrent cost study could be undertaken.*



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Timeframe for Research and Cost Study

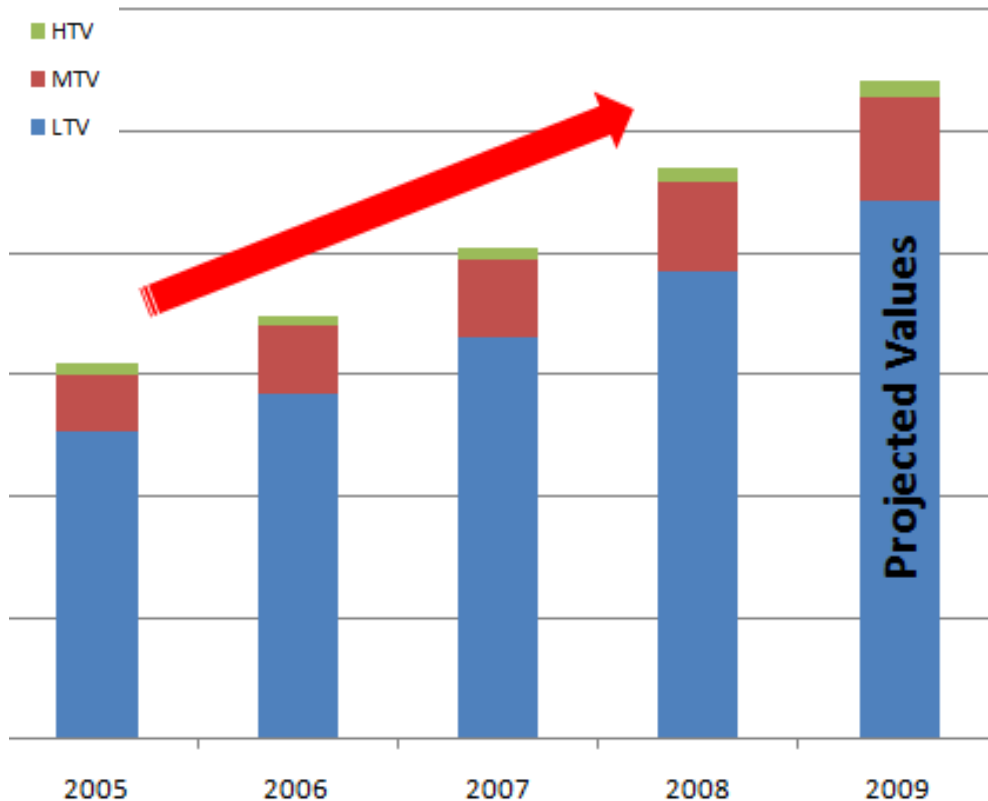


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- **Current Demand Data**

Equipping Our Soldiers in Iraq and Afghanistan



The size of the tactical fleet has been growing exponentially for the past 3 years.

The level of protection (transparent and opaque) continues to increase due to increased threats.

More vehicles = More glass

Early OIF



Curb Wt: 10,300lbs
GVW: 12,100lbs

More Vehicles
More Attacks
More Glass

2004-2005 GPK
(Gunner Protection Kit)



2006
“Iraqi Pope Glass”

Requirement:

Upgrade GPKs with transparent armor for enhanced situational awareness while maintaining soldier cover within armor envelope.

Baseline



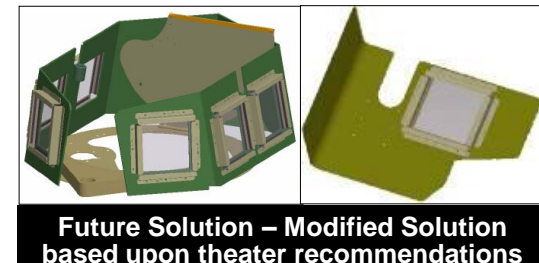
Interim



Initial

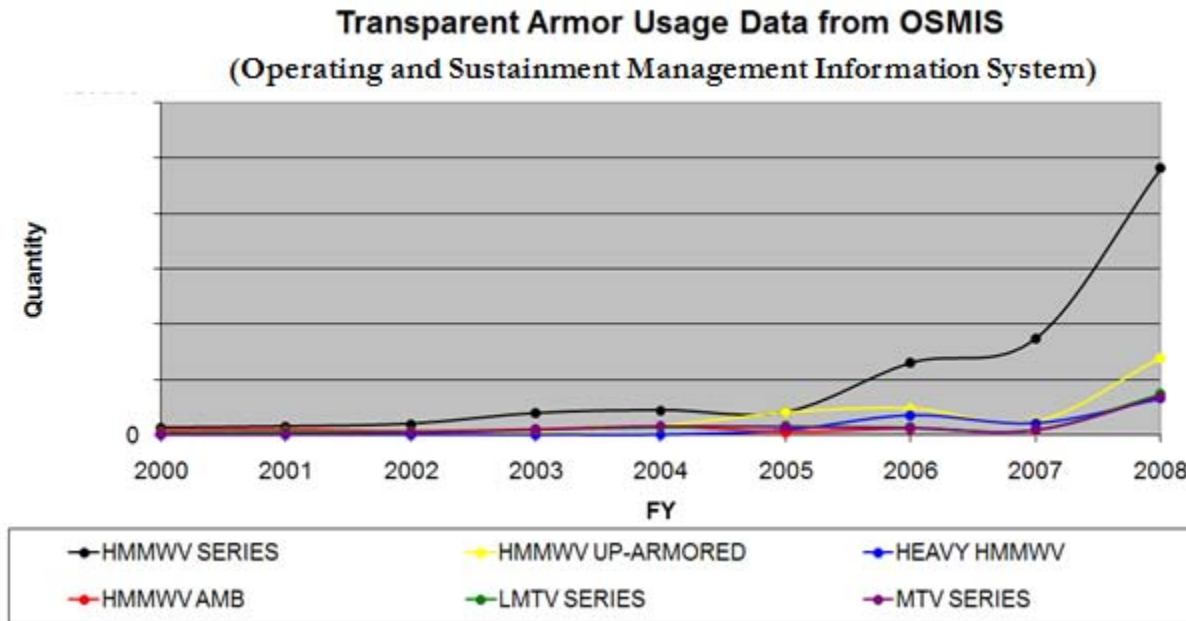


Objective



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Tactical Vehicle Glass Demand



• Average Total (\$) for transparent armor increased by about 20% (each year) from FY06-08.

• Average Demand (qty) for transparent armor increased by about 70% (each year) FY06-08.

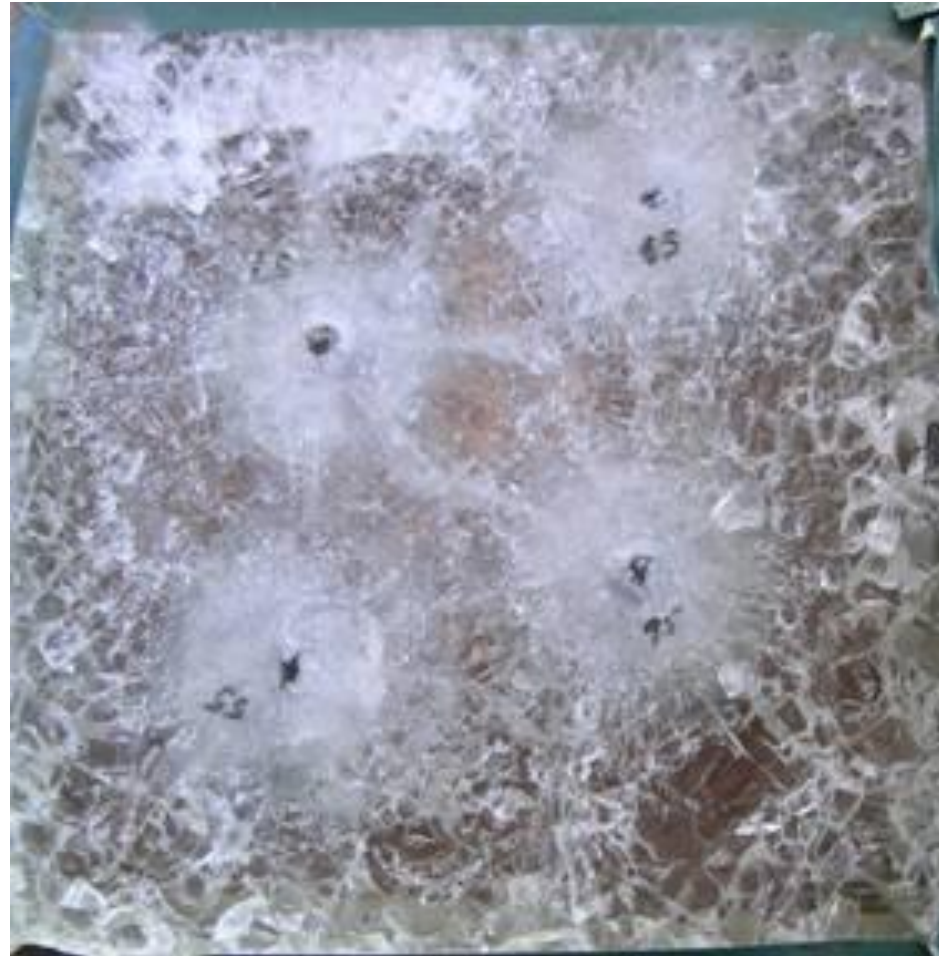
• \$110,000 per day was spent during FY06-08 for the tactical fleet's transparent armor.

• **Bottom Line:** *Army needs an improved transparent armor solution!*

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Causes of Current Glass Failure

- Insurgent Attacks – wide range of threats
- Sandstorm Damage
- Rock Strikes
- Improper removal/installation
- Clouding
 - Delamination from environmental degradation
 - Improper curing process
 - Improper cleaning



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- Each year, AMSAA (Army Materiel Systems Analysis Activity) collects detailed data on a specific set of vehicles by serial number.
- Data collectors embedded within units to collect various data elements
 - OPTEMPO
 - Part Replacements
- Requested glass data be collected over a 4-month period
 - Date of Incident
 - Vehicle Model
 - NSN
 - Serial Number
 - Location
 - Window Type
 - Failure Type
 - Remarks
- Provided pictures in some cases

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- 266 damage incidents
 - 115 M1114
 - 151 Other
 - 44 M1070
 - 44 M915A3
 - 63 Misc – ASV, M1130, Other HMMWV, FMTV, etc.
- 6 damage categories
 - Combat, Sand Storm, Rock Strikes, Clouding, Delamination, Installation



M1114 – Up-Armored HMMWV



M1070 – Heavy Equipment Transporter Tractor



M915A3 – Light Equipment Transporter



ASV – Armored Security Vehicle



M1130 – Stryker Commander's Vehicle



FMTV – (Light) Medium Tactical Vehicles

Approaches with one categorical data set:

- Histogram of data set to visualize data
- Some statistical bounds on the average value of each category's expected value (%) based on sample size and the desired confidence

Average Category Value (%)	Sample		
Category	All	M1114	Other
COMBAT DAMAGE	62.8%	71.3%	56.3%
SAND STORM DAMAGE	0.0%	0.0%	0.0%
ROCK STRIKE	31.6%	25.2%	36.4%
IMPROPER INSTALLATION	0.0%	0.0%	0.0%
CLOUDING	3.4%	3.5%	3.3%
DELAMINATION	2.3%	0.0%	4.0%

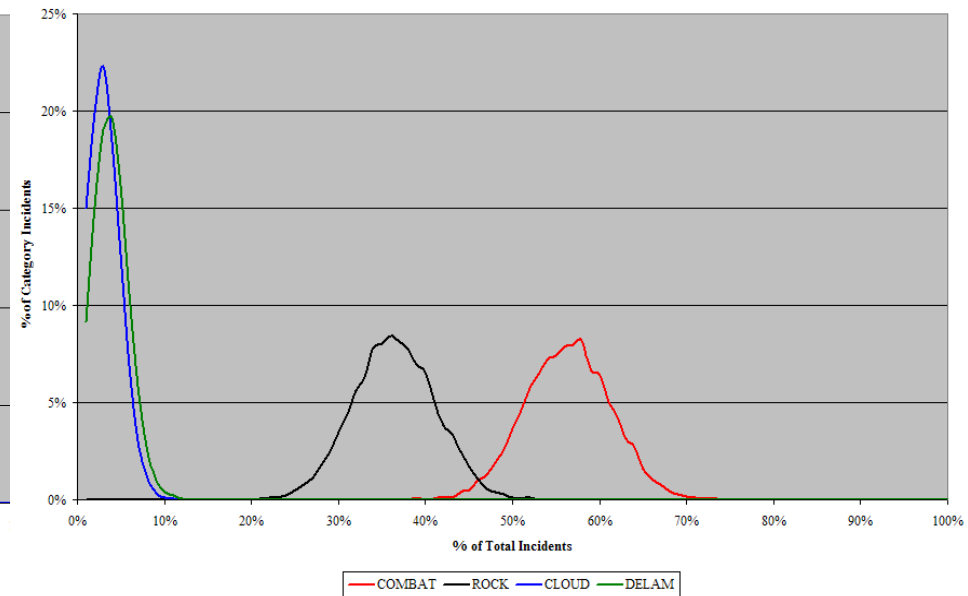
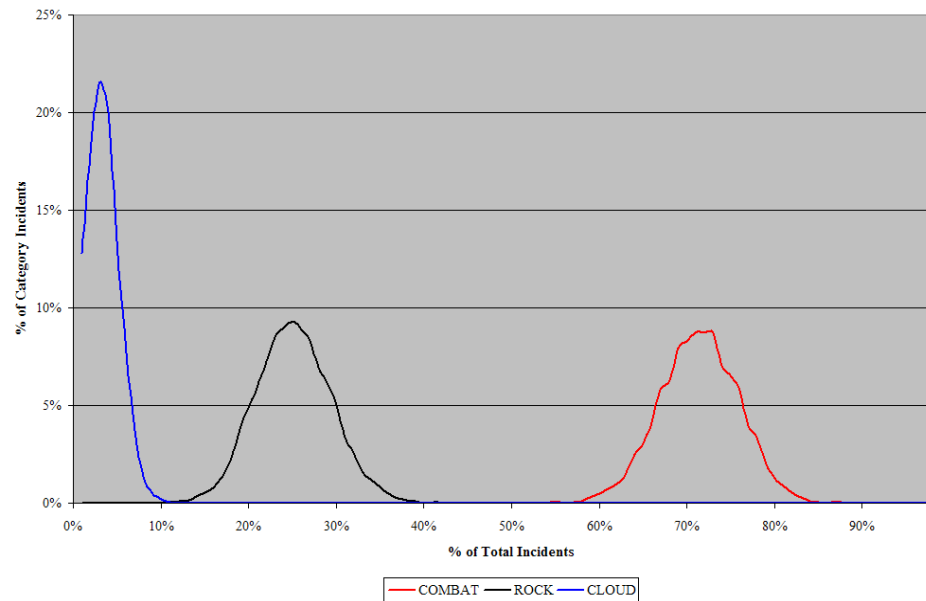
Bound on Average	Confidence Level		
Sample Size	90%	95%	99%
266 (All)	± 5%	± 6%	± 7.9%
115 (M1114)	± 7.7%	± 9.1%	± 12%
151 (Other)	± 6.7%	± 8%	± 10.5%

Other Analysis

- One sample histogram data doesn't give a good visual picture or idea of what possible values could be.
- One way to get a distribution profile that models the sample data is to resample using the bootstrap technique.

M114 Transparent Armor Damage Profiles

Other Variant Transparent Armor Damage Profiles



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Problems with Current Glass Favoring a Ceramic Based Solution



- Current glass solution adds significant weight to vehicle
- Thickness of glass can cause distortion and glare

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Future Transparent Armor Solutions



<u>Cause of Failure</u>	<u>Potential for Improvement over Current Armor Solution</u>
Insurgent Attacks	Depends on Threat
Sandstorm Damage	Yes
Rock Strikes	Yes
Improper removal and installation	Yes
Clouding	
- Delamination environmental degradation	Yes
- Improper curing process	Yes
- Improper cleaning techniques	Yes

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Other Potential Benefits of a New Transparent Armor Solution



	Impact
Vehicle Weight	↓
Logistics Footprint	↓
Crew Survivability	↑
Operational Availability	↑
Safety Related Accidents	↓

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- **Government Cost/Benefit Analysis**

Purpose: Determine break-even cost for new transparent armor solution based on expected reliability improvement and required investment.

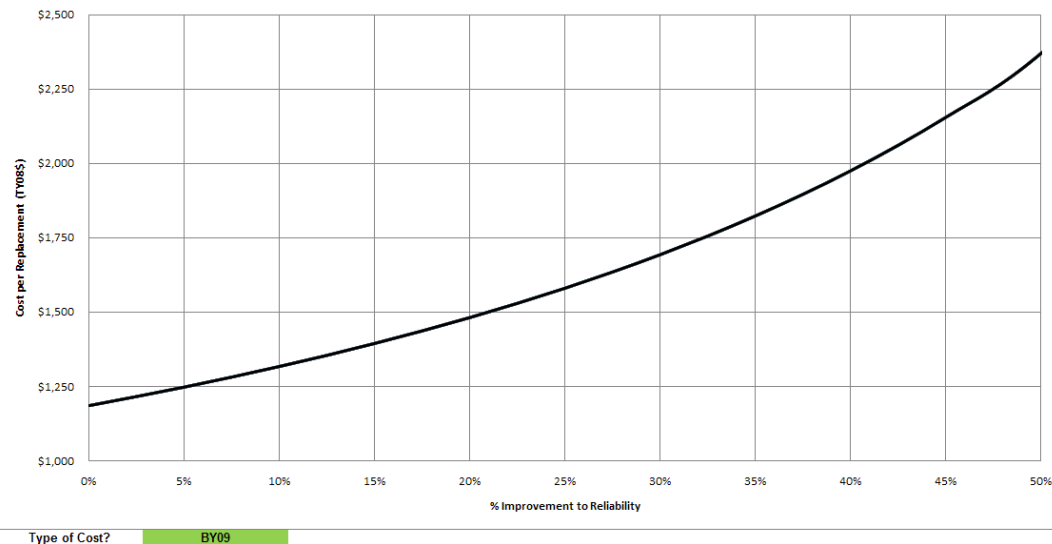
- Current fleet used as initial study platform (11,000+ vehicles)
- NSN 2510-01-435-9690/3 – L/R Windshield
 - \$2,759 (FY06\$)
 - \$1,075 (FY09\$)*
- NSN 2510-01-435-9692 – Door Window
 - \$1,025 (FY06\$)
 - \$ 474 (FY09\$)*



**Costs have decreased due to an increase in volume and the number of approved suppliers.*

Cost-Benefit Methodology

Reliability-Cost Breakeven Curve for M1114 Windshield



Obtain current demand data and cost data to determine operations cost for status quo.

Obtain investment costs for new transparent armor solutions.

Collect field data to determine distribution of failures.

Parametric Analysis

Determine improvement for new transparent armor solutions

Determine break-even point on curves.

Curves based on 2007 demand data from initial study (Phase I).

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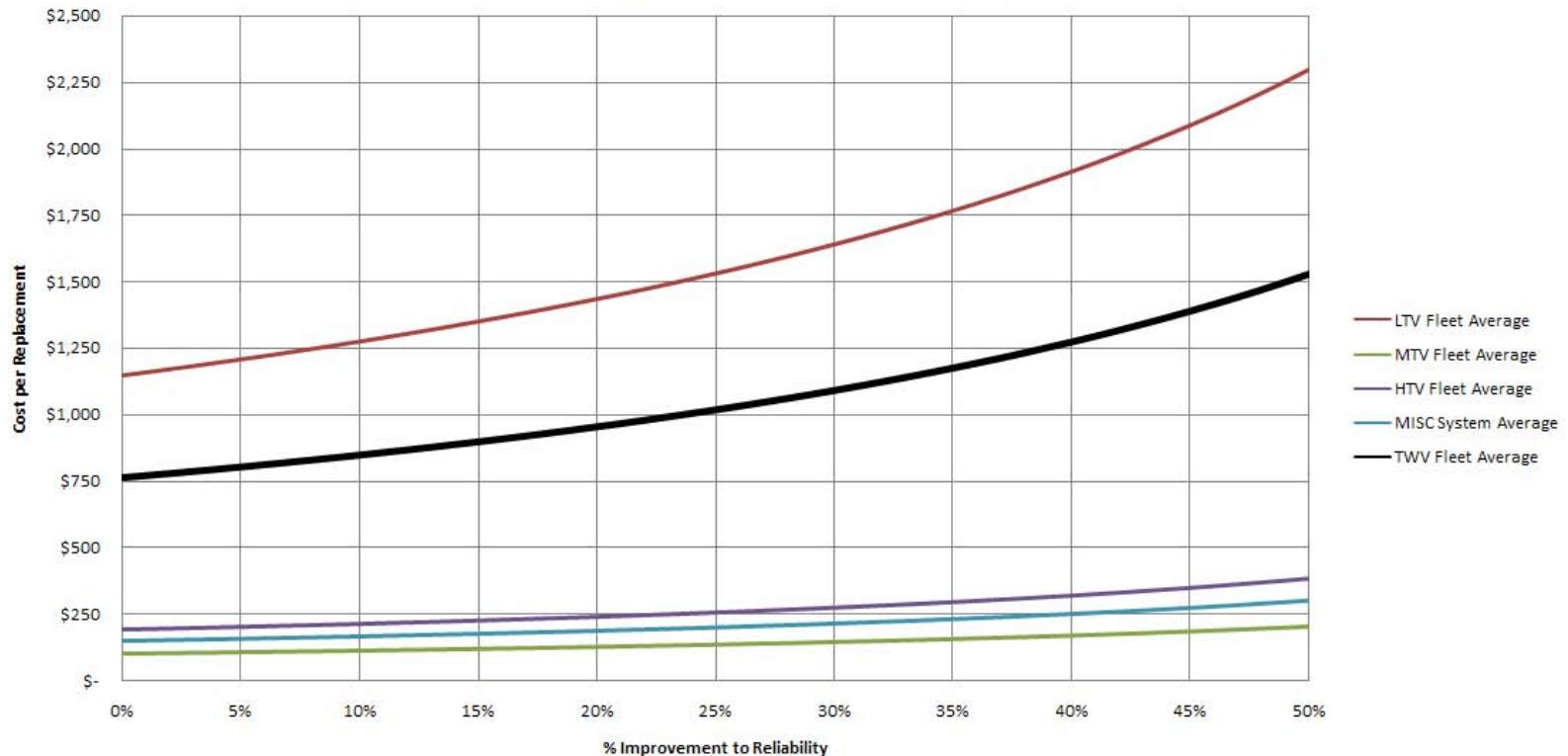


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Cost-Benefit Parametric Analysis: Expanded to Tactical Fleet Glass



TWV Cost-Reliability Breakeven Curve (Average FY2000 - 2007)



Type of Cost? BY09

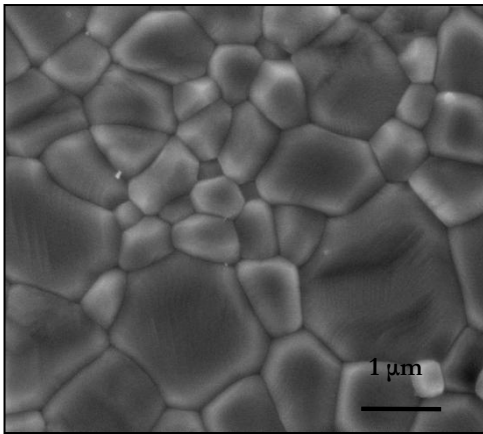
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- **Ballistic Depth of Penetration (DOP) Test**

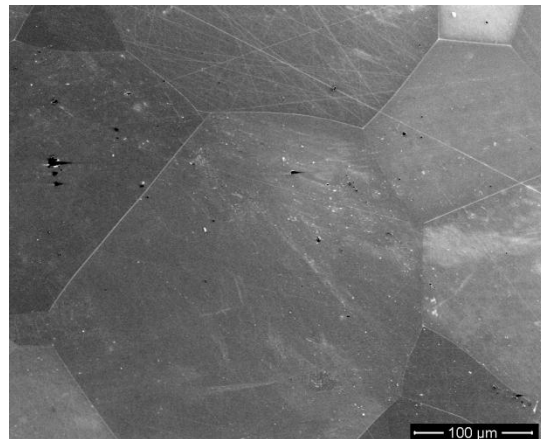
- **Achieved* Nanostructured Spinel**
 - average biaxial flexural strength > 480 MPa
 - grain size < 2 μm
 - > 80% in-line transmittance at 632 nm wavelength, 3/8" thick samples

Dry pressed, pressureless sintered
+ HIP'ed Spinel



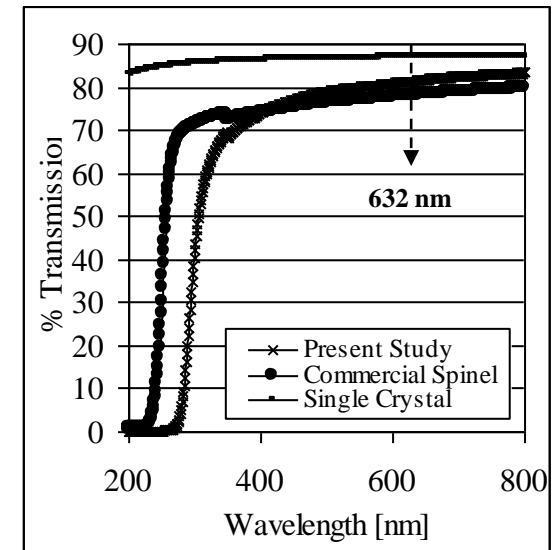
Average grain size ~1.4 μm

Commercially-available hot pressed
+ HIP'ed Spinel



Average grain size >50 μm

Specular transmission normalized to
9.6 mm thickness



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Initial Ballistic DOP* Test 3" disks

Glass Baseline Ballistic Test



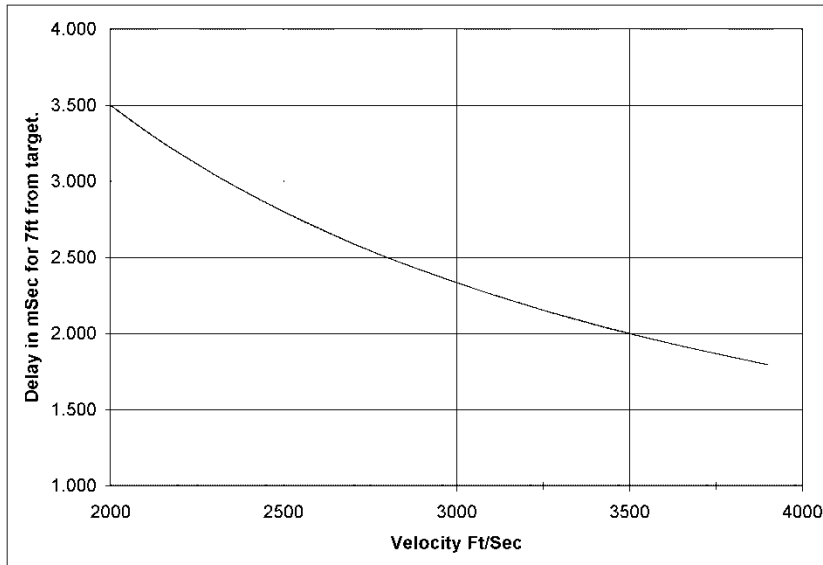
Penetrator

Spinel Comparison Ballistic Test –
to be continued

“Commercial”



Nanostructured



*TARDEC, Dr. David Nelson Hansen, Mr. Terry Avery, Mr. Matthew Magner

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- **TARDEC and TACOM took up the challenge to develop a tool for decision makers to find the break-even cost for new materials that improve transparent armor performance**
- **The initial Cost-Benefit Methodology for the M114 (HMMWV) Windshield has been extended to the Tactical Fleet Glass**
- **A two-phase, 26 month basic research effort yielded a nanostructured, spinel with $> 80\%$ in-line transmittance in the visible range**
- **Ballistic DOP tests comparing commercially available large grained spinel with nanostructured spinel are in-process at TARDEC**